OPTICAL INSPECTION METHOD AND APPARATUS HAVING AN ENHANCED HEIGHT SENSITIVITY REGION AND ROUGHNESS FILTERING

RELATED APPLICATIONS

This application is related to pending U.S. Patent Application serial number 09/789,913 entitled "SYSTEM OF BEAM NARROWING FOR RESOLUTION ENHANCEMENT AND METHOD THEREFOR" filed on February 21, 2001, the specification of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

This invention relates to optical inspection systems, and more specifically, to an optical system incorporating a resonator to produce an enhanced sensitivity to defects with significant height and a filtering of surface roughness.

DESCRIPTION OF THE RELATED ART

Precision surfaces are required in components used in many applications today. Storage media for use in both for optical and magnetic storage systems require surfaces that are free of

defects having significant height above the mean surface of the media. If a defect sufficiently high collides with the storage system head assembly, the storage system may be destroyed or damaged.

In semiconductor manufacturing, semiconductor material is etched from and deposited on a silicon wafer. Yield of semiconductors is dependent on defect-free regions on the surface of the wafers. Defects of significant height may cause shorting between layers within an integrated circuit and may also reduce reliability of integrated circuits that appear otherwise functional after manufacture.

In the manufacturing process, it is necessary to inspect media, wafers and other surfaces to determine whether or not they are manufactured to the tolerances demanded by functional requirements and to make necessary adjustments in the manufacturing process to avoid manufacturing defective components.

Near field inspection systems may be used to resolve small defects, but since the near-field is confined to a relatively small height above the surface under inspection, it must scan

the surface very slowly to avoid collision with the surface and if defects of significant height exist, the near-field probe may be damaged by collision with a defect.

Present far-field inspection systems use interferometric techniques to determine surface height by reflecting and measuring an optical beam off the surface under inspection. However, standard far-field inspection systems are unsuitable for detecting small profile defects having significant height above the average surface.

Any optical inspection system has resolution limits. Within a resolution cell dictated by the resolution limits, the reflected field will be averaged from all points within the aperture of the resolution cell. The resolution cell limits are both angular and linear and are affected by surface characteristics in that very small surface features disperse a reflected field over a wide angle. Small sub-wavelength defects and surface variations approach point source behavior, which will cause reflected energy to be dispersed throughout a half-plane (180 degree solid angle) above a surface under inspection.

Within the resolution cell of an optical inspection system, the received reflected energy is averaged. A defect that is significantly smaller than the resolution cell and having a height or depth that is slightly greater than the acceptable surface roughness will produce an optical signal that is indistinguishable in the presence of the "speckle noise" produced by the surface roughness.

Due to the angular spectrum of small defect reflections (reflecting into approximately the entire half-plane) and the resulting interference with surface roughness variations within the resolution cell being measured, the sensitivity of existing far-field inspection systems to small (sub-wavelength) defects is further reduced.

In essence, a wide-profile deviation of nominal depth or height that is acceptable, may produce the same or greater inspection signature as a very small-profile defect of unacceptable height. Therefore existing far-field optical systems cannot discriminate between small defects and normal roughness variations. Thus, existing far-field optical inspection systems are unsuitable for inspecting surfaces for small defects. Since the profile of a defect that may cause

damage to a media storage device or shorting in an integrated circuit wafer may be very small, existing far-field inspection systems are unsuitable for detecting the above-mentioned defects.

Therefore, it would be desirable to provide a far-field inspection method and apparatus having an enhanced sensitivity to defect height. It would further be desirable to provide an inspection method and apparatus having a filtering characteristic for reducing the impact of surface roughness on inspection sensitivity. It would further be desirable to provide a far-field inspection method and apparatus that reduce the angular spectrum of reflections from a small defect to improve discrimination between small defects and surface roughness.

SUMMARY OF THE INVENTION

The foregoing objectives are achieved in an optical inspection method and apparatus having an enhanced height sensitivity region and roughness filtering. The inspection apparatus includes an optical illumination system for producing a beam for illuminating a surface under inspection, a detector for detecting intensity of light reflected from the surface under inspection, and a partially reflective surface positioned between the illumination subsystem and the surface for forming an optical resonator between the partially reflective surface and the surface under inspection. The resonator improves the sensitivity of the detector to reflections from defects having a height exceeding a predetermined height. The sensitivity is increased due to multiple reflections within the resonator. The resonator may be tuned so that the sensitivity of the inspection system is decreased for surface variations below a predetermined value and increased for variations above the predetermined value, so that filtering of acceptable roughness variation is achieved. The resonator also reduces the angular spectrum of reflections from small defects.

The foregoing and other objects, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the invention, as illustrated in the accompanying drawings.

Brief Description of the Drawings

Figure 1 is an illustration depicting a cross section of a surface under inspection by a prior art inspection system.

Figure 2A is a graph depicting optical images generated by prior art inspection system **10** of **Figure 1**.

Figure 2B and **Figure 2C** are graphs depicting the sensitivity of the prior art system of **Figure 1**.

Figure 3 is an illustration depicting a cross section of a surface under inspection by an apparatus in accordance with a preferred embodiment of the invention.

Figure 4A and **Figure 4B** are graphs depicting the enhanced sensitivity of the system of **Figure 3**.

Figure 5 is an illustration depicting a cross section of a surface under inspection showing an improvement in angular selectivity generated by an apparatus in accordance with a preferred embodiment of the invention.

Figure 6 is a block diagram depicting details of the apparatus of **Figure 3** inspecting a surface.

Description of Embodiments of the Invention

With reference now to the figures, and particularly to **Figure 1**, a surface **11** under inspection by a prior art far-field optical inspection system **10** is depicted. Optical inspection system **10** is commonly known as an interferometric contrast microscope. Optical inspection system **10** includes a detector **12** shown here as a charge-coupled device (CCD) linear array, but other suitable detectors may be used. A lens **19** images light reflected from a resolution cell **13** on surface **11** to a cell of CCD **12**. The illumination path is not depicted in the illustration, nor is a reference path, as it is the reflected light that is pertinent to the description of the differences between the prior art and the present invention. Several resolution cells may thereby be scanned by detector **12** without moving the inspection head. Resolution cell **13** represents the optical resolution of imaging lens **19**.

An illumination beam (not shown) is reflected by surface **11** to produce a reflected beam **14A**. The reflected beam is comprised of wavefronts from surface **11** including reflections from surface variations **14B** and reflections **14C** from a defect **15**. The resolution aperture **13** encompasses all of the above reflections,

vector summing each of the reflections. Resolution aperture **13** in practice is much larger than defect **15**, but the size of defect **15** has been increased in the figure for illustrative purposes.

In the vicinity of surface features (roughness, defects, etc.), speckle noise is produced, creating a field that extends over aperture **13**. While it would be desirable to use a far-field system such as optical inspection system **10** for high-speed scanning of such surfaces as storage device platters, it is not practical due to the inability of optical inspection system **10** to distinguish small-profile defects such as defect **15** that are of a height greater than an acceptable threshold **16**.

Since optical inspection system **10** via detector cell **12** averages all of the reflections received from resolution cell **13**, and since defect **15** is significantly smaller than resolution cell **13**, defect **15** will produce an optical signal that is indistinguishable in the presence of the speckle noise produced by the surface roughness.

For example, assume optical inspection system **10** has a resolution of 2μm and inspects a surface having a roughness

variation of .002μm peak-to-valley with an acceptance/defect limit of .01μm height. If defect **15** has a diameter of 0.2μm in the plane normal to surface **11**, the area of defect **15** is approximately 1% of the resolution cell area. Although the height of defect **15** is greater than the roughness variation by a factor of 5, the speckle noise will be greater than the optical signal from defect **15** by a factor of 20, as the roughness signal (producing speckle noise) extends over the resolution cell which has an area greater by a factor of 100.

Therefore, standard far-field inspection systems such as prior art far-field optical inspection system **10** are unable to detect defects that will render a surface unacceptable or needing modification via machining, laser modification or other technique.

Referring now to **Figure 2A** the above-described problem with prior art far-field measurement systems is depicted in graphical form. The graph shows relative intensity of the response of the received optical signal as a function of the surface displacement relative to the optical inspection head. Curve **RF1** shows the response from an ideally flat reflective surface. Curve **RF2** shows the maximum expected deviation of the image

signal due to surface roughness for one position of the inspection head (or roughness location), while curve **RF3** shows the maximum expected deviation of the image signal in the other direction, for a different position of the inspection head. The actual signal variations due to acceptable surface roughness are expected to fall between curves **RF2** and **RF3**. A significant deviation from this range indicates the presence of a defect. Curve **RF4** shows the same image as curve **RF3** for a surface having a small defect within the resolution aperture. As can be seen from the graph, the deviation of the image signal in the presence of a defect is slight with respect to the deviations due to normal surface roughness. For the case illustrated, the deviation signal variation lies within the range of acceptable roughness signal variation and therefore, the defect is not detectable using an inspection system having the above-described characteristics.

Referring now to **Figure 2B**, the underlying low sensitivity of prior art far-field measurement systems to small height variations is depicted in graphical form. As seen in the graph, variation in detected signal power continuously increases for height variations from zero to over 3000 nanometers, from which the power returned is twice the laser power (for a totally

reflective surface). However, the surfaces of interest in storage media and other applications may fall in the range of the graph below 20 nanometers, where the energy returned is miniscule.

Referring to **Figure 2C**, the region of interest from **Figure 2B** is expanded and is depicted for a system wherein the interferometric contrast is optimized for height variations below .02μm (otherwise the slope of the signal curve would be even lower, resulting in a lower sensitivity to small height variations). As can be seen from the graph, the signal around the average surface profile is practically linear and is still very small with respect to the total laser power, approaching a 2% return for height variations approaching .02μm (20 nanometers).

The above-illustrated example can be analyzed using the graph of **Figure 2C.** A defect .01μm high with an area of 1% of the resolution aperture with a surface roughness of .002μm peak-to-valley yields a peak-to-peak roughness signal (noise) of .25% and a defect signal component of .01%, yielding a peak signal-to-noise ratio of -13dB, (1:20) indicating that the signal from the defect is undetectable in the presence of surface roughness.

Referring now to **Figure 3**, surface **11**, under inspection by an enhanced optical inspection system **20** in accordance with a preferred embodiment of the present invention is depicted. A partially reflective surface **26** is incorporated within optical inspection system **20** producing an optical resonant cavity between partially reflective surface **26** and surface **11** under inspection. The resonance of the cavity is inherently highly non-linear and therefore it is possible to adjust the length of the cavity by varying the position of the partially reflective surface **21** to enhance a filtering effect. The filtering effect filters a reflected field from the surface, based strictly on the height of the surface.

Enhanced optical inspection system **20** includes a detector **27**, which is depicted as a CCD array, although other suitable optical detectors may be used. A lens gathers reflected wavefronts **24A-24C** from surface **11** and images the resolution cell **23** on surface **11** on CCD pixel **22** which averages the light reflected from resolution aperture **23**. Reflected wavefront **24A** represents the entire range of reflections from resolution aperture **13**, while reflected wavefront **24B** depicts a reflection from a roughness area and wavefront **24C** depicts a reflection from defect **15**. Note that in contrast to the illustration in

Figure 1, reflection **24C** from defect **15** does not overlap reflection **24B** from the roughness area and can therefore be more easily resolved by detector **27.** The multiple reflections set up in the resonant cavity formed by partially reflective surface **26** and surface **11** are highly sensitive to angle, and therefore serve to separate reflections from surface features displaced from each other. Due to the small angular spectrum accepted by the resonant cavity, surface feature reflections will sum in image pixel **22** in a non-coherent manner, causing any interferences to be uncorrelated, significantly decreasing optical noise from surface **11.**

The resonance of the cavity is inherently highly non-linear and therefore it is possible to adjust the length of the cavity to provide filtering of reflections based on surface height. The position of partially reflective surface **21** can be adjusted so that a resonance condition tuned to produce a higher overall reflected energy return for height variations within a region of interest (for example, 5 to 20 nanometers) and having a non-linear response with respect to height variation. The non-linear response produces a filtering effect. The filtering effect can be tuned to produce little signal variation for height variations below, for example, 5 nanometers, providing a

rejection of most of the surface roughness variation, while returning a strong signal from defects having a height greater than 5 nanometers.

Due to the filtering effect and reduction in the field coupling between surface features, defect **16** can be detected as having a height exceeding acceptance threshold **15**, by the techniques of the present invention. Thus, enhanced optical inspection system **20** can achieve results similar to a near-field inspection system, without placing a probe within the near-field region, by filtering out all of acceptable height variations.

Referring now to **Figure 4A**, the operation of the present invention is depicted in graphical form. For very low height variations, little or no laser power signal is detected, but above a threshold, the laser power returned increases rapidly to very high values. Thus, the detector sensitivity may be improved for inspecting surfaces having a region of interest for height variations, and the non-linear response for small height variations may be used to filter out acceptable surface roughness.

Referring now to **Figure 4B**, the operation of the present invention over the exemplary region of interest is depicted. For height variations below 2 nanometers (from 100.261μm to 100.263μm on the graph), the signal variation with surface height is small, but above 2 nanometers(from 100.263μm to 100.283μm), the slope becomes linear and increases rapidly. Due the non-linear response of the resonant cavity to small height variations, the system will filter height variations bellow a given threshold and enhance all others. Note also the large signal comparative to the regular phase contrast - Figures 2A and 2B. The nonlinearity range of the resonant cavity depends on the reflectivity of the two surfaces forming the cavity and on the absorption of the tested surface.

From the graph depicted in **Figure 4B**, a feature having a height of 20 nanometers will return approximately 55 percent of the laser power, while surface roughness below 2 nanometers will integrate to a much lower value than in the prior art system. Additionally, the reduction in field coupling to other surface features reduces the range of the surface features contributing to the roughness variation so that a 10 nanometer high defect will "stand out" in the detected signal.

The resonance condition between surface **11** and partially reflective surface **26** also reduces the angular spread of reflected beams **24A-24C**, producing a system response that is much narrower than the reflected beams **14A-14C** of **Figure 1** and system sensitivity to the interaction between closely spaced features creating speckle noise is greatly reduced. Referring now to **Figure 5**, the improvement in angular rejection is illustrated. Between partially reflective surface **26** and surface of interest **11**, the angles for which the resonance condition are supported are those angles very close to the axis normal to both surfaces, as both surfaces must be kept parallel. Thus, the angular spread of reflection **24C** from defect **15** that is enhanced by the resonance condition is much smaller that the angular spread of reflection **14C** from defect **15** in prior art optical inspection system **10**. While in the prior art system, energy reflected from defect **15** will be spread through a wide angle, the resonance condition present in embodiments of the present invention ensures that most of the energy will be concentrated at angles very close to the normal axis between surface **11** and partially reflective surface **26**.

Referring now to **Figure 6**, details of enhanced optical inspection system **20** are depicted. Illumination subsystem **31** produces a beam **22** that is directed at surface under inspection **11** through partially reflective surface **26A.** Partially reflective surface **26A** produces a Fabry-Perot optical resonant cavity with surface under inspection **11.** At the distance at which partially reflective surface **26A** and surface under inspection **11** form the optimal Fabry-Perot cavity, the sensitivity is greatest, due to the resonance condition of the Fabry-Perot cavity. Detection subsystem **33** provides detection of the reflected beam, permitting measurement of surface height variations. The presence of partially reflective surface **26A** increases the sensitivity of the interferometer around the resonant distance of the Fabry-Perot cavity formed between the partially reflective surface **26A** and surface under inspection **11.**

A second tier **26B** to partially reflective surface **26A,** may be incorporated to provide a second resonant cavity having a second resonant length disposed around the central resonant cavity. This second resonant cavity is used for position control, permitting operation of detectors for determining surface tilt and average height at a separate operating point

within the curves of **Figure 4A** and **4B**. For example, a resonant distance set by second tier **26B** that is 8 nanometers longer than resonant length set by partially reflective surface **26A**, will result in a signal strength of 25% of the incident light and a sensitivity (slope) that is at a maximum for the graphs in the figures. This permits a pair of detectors, a quad photodiode array or a CCD detector to detect a second strong signal angularly disposed outside the circumference of the height detection central area for adjusting the position of partially reflective surface **26A** (and consequently second tier **26B**). If a CCD linear array detector is used, the intersections of the resonant band (annular) due to second tier **26B** will be detectable at a pair of cells surrounding the cells receiving signal from the central area, thus the same detectors that are used for detecting the height-measuring interferometric signal at other positions within the scan may be used at other times for detecting surface tilt and average position.

Partially reflective surface **26A** (and optionally second tier **26B**) may be a lens within illumination subsystem **31** that may be positioned by positioners **35A** and **35B** and position control **38**, a separate partially reflective plate again

positioned by a positioners **35**, or a coating or plate placed directly on surface under inspection **11**.

A control subsystem **38** and position control **39** are used to move positioners **35A** and **35B** that are mechanically coupled to partially reflective surface **26A**. Positioners **35A** and **35B** move partially reflective surface **26A** (and consequently second tier **26B**) to positions that track surface variations in order to maintain the resonance condition between partially reflective surface **26A** and surface under inspection **11**, so that the filtering effect and contrast enhancement are provided at the desired height above the average surface height. Positioners **35A** and **35B** likewise maintain the second resonance condition between the surface and second tier **26B** (if incorporated) to maintain maximum position detection sensitivity.

A processing system **37** is coupled to detection subsystem **33** and position control **39**, for controlling the position of partially reflective surface **26A** in conformity with information received from detection subsystem **33**. Processing system **37** may thereby adjust the position of partially reflective surface **26A** to maximize the detection sensitivity for inspection of a region having a tilt or surface variation, which maintains the

filtering effect and sensitivity in the region of interest. Detection subsystem may use multiple detectors **34a - 34c** aligned in different planes to detect surface tilt and height, such as the quad photodiode array mentioned above, or detection system may incorporate a linear CCD array and use peripheral cells to determine position and tilt. Position control **39** as configured moves positioners **35A** and **35B** independently to tilt and move partially reflective surface **26A** to maintain a substantially parallel arrangement between partially reflective surface **21** and the region of surface under inspection **11** that is within the aperture of the optical inspection system.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form, and details may be made therein without departing from the spirit and scope of the invention.